Processes Controlling Transfer of Fine-Grained Sediment Within and Between Channels and Flats on Intertidal Flats

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Award Number: N00014-10-1-0213
http://tidalflats.org

LONG-TERM GOALS

A long-term goal of our sediment transport and accumulation investigations is to link sediment-transport processes to the formation and preservation of event beds in sediment deposits. The general aim of this project is to investigate how forcing processes affect the sediment-transport dynamics that act to import or export fine-grained sediment in intertidal regions. We strive to understand how the delicate balance of ebb and flood sediment fluxes is maintained to create a stable (or unstable) tidal flat complex that is characterized by tidal channels and variable seabed stability. Our goal is to answer the question: What influence do tidal (semidiurnal, fortnightly), riverine and other seasonal (winds/waves, precipitation temperature, and biological) processes have on the transfer of sediment between tidal-flat environments, and how is this manifested in terms of channel and flat deposits?

OBJECTIVES

The dominant processes that control terms in the budget of sediment on tidal flats include advected input from rivers, precipitation on exposed flat surfaces, erosion/deposition at the seabed, and transport of sediment in and out of each sub-environment (e.g., primary/secondary channels, flats). Our studies seek to evaluate these processes over time scales from tidal and event (e.g., storms) to seasonal and interannual. We seek to address the following objectives:

1. Evaluate the dynamics of <u>water-column sediment-flux</u> and the controls by physical (e.g., wind, precipitation, river discharge), sedimentological (sediment grain size and erodibility) and biological (vegetation and benthic biota) processes.
2. Relate water-column sediment-flux dynamics to <u>seabed changes</u> in bed elevation, porosity and grain size (resulting from deposition, erosion, bioturbation and dewatering/desiccation).
3. Determine the <u>linkages between environments</u> (e.g., exchange between flats and channels) through spatial studies of bed stress, sediment flux and suspended-sediment characteristics.
4. Foster <u>scientific interaction</u> with other ONR Tidal Flat participants. This includes investigators who are focusing on seabed processes, remotely observed signatures, and numerical modeling.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**
4. TITLE AND SUBTITLE **Processes Controlling Transfer of Fine-Grained Sediment Within and Between Channels and Flats on Intertidal Flats**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,School of Oceanography,Box 357940,Seattle,WA,98195**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

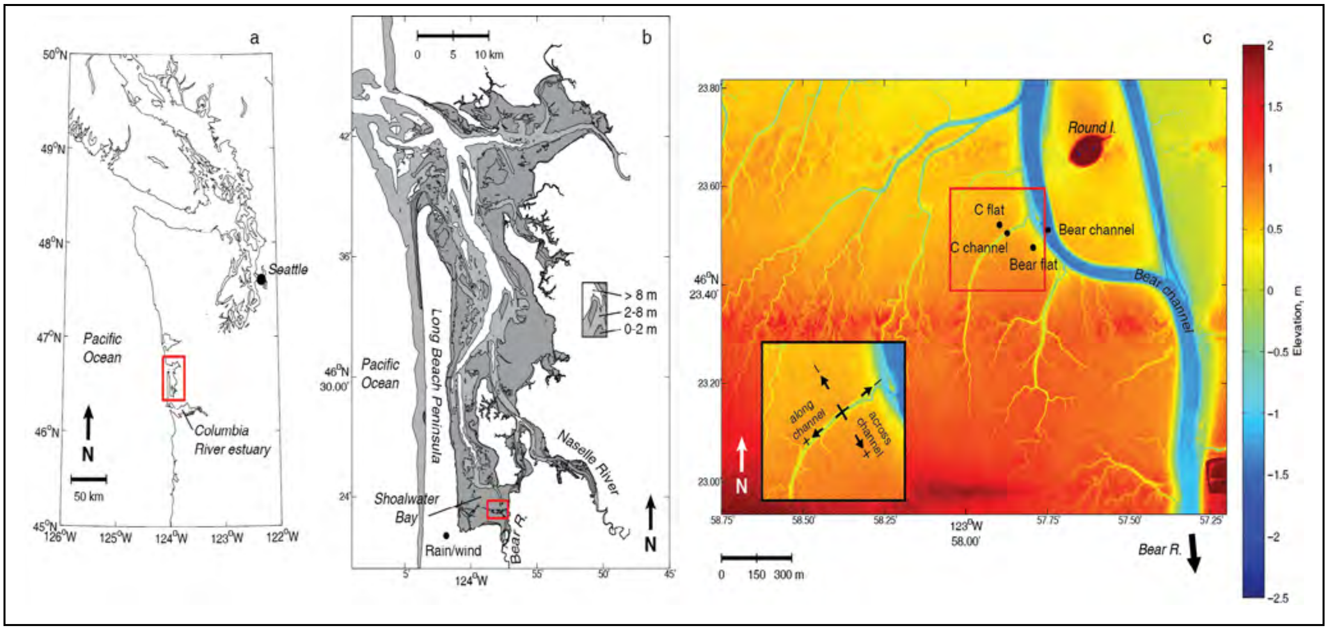

Figure 1. (a) Map of the Pacific Northwest coastal region, with Willapa Bay indicated by red square. (b) Willapa Bay bathymetry, with study area indicated by red square. (c) Study area map showing elevations produced from LiDAR data collected in 2002 (Buijsman et al., 2002) and instrument locations indicated by black circles.

APPROACH

Our work under the Tidal Flats DRI has focused on the processes controlling the transfer of fine-grained sediment within and between channels and flats on two contrasting meso-tidal flat environments. The primary study site is in Willapa Bay (Fig. 1), a muddy embayment in SW Washington that is tidally dominated and receives relatively little direct freshwater influence. This study area allows us to focus on asymmetries in tidal processes. In comparison, the Skagit River tidal flats (NW Washington; see Results) have similar tidal and wind forcing, but are dominantly composed of sand and have a large river input of freshwater and sediment.

Tidal-flat studies require specialized sensors and platforms designed to capture the processes and resulting seabed structures without impact to the soft seabed, particularly in the muddy environment of Willapa Bay. For time-series studies, we have deployed instrument suites on small frames that have minimal impact on the sediment-water interface (Fig. 2).

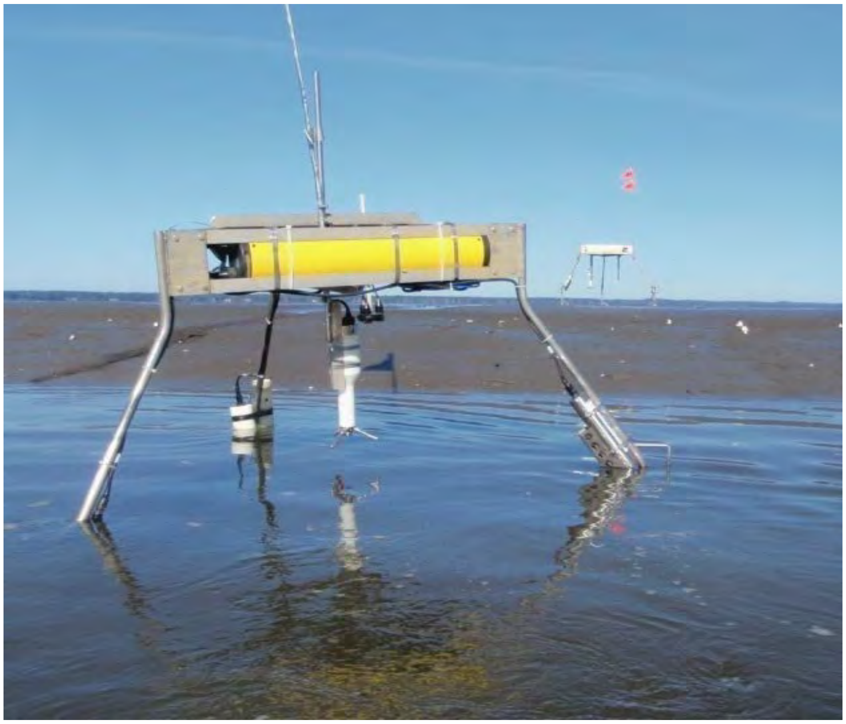

Figure 2. Photo of paired channel/flat instrumentation packages deployed in C Channel and the nearby flat surface on the Willapa tidal flats.

We have developed a platform that allows mobile access at high to mid tides and creates a stationary sampling area when deployed as a jack-up barge, leaving the seabed undisturbed at low tides. Additionally, new sensor systems have been developed that allow us to investigate the brief periods in which much of the sediment flux occurs -- when water depths are very shallow on the flats.

WORK COMPLETED

Field work at Willapa Bay was completed in fall, 2010. A long-term instrument package was deployed for two years in a primary channel, and focus experiments were accomplished seasonally. The main site of investigation for all the Willapa Tidal Flats participants was on a secondary channel (channel C; Fig. 1), but during the winter focus experiment, both the primary (Bear Channel) and the secondary channel were instrumented. At the Skagit Bay site, field work was conducted as a seasonal focus experiment at two sites on the outer part of the tidal flats, one off the north fork and one off the south fork to study shallow intertidal processes. During the year covered in this report, the emphasis has been on data analysis, integration of results, and publication. Four publications have been submitted to a *Continental Shelf Research* special issue on Tidal Flats. These papers have been favorably reviewed and are expected to be published in late 2011 or early 2012. Two more publications are in preparation. The major scientific findings are presented below in “Results” as summaries of discussion points from the manuscripts. In addition, numerous presentations have been made (see “Publications” for those with printed abstracts).

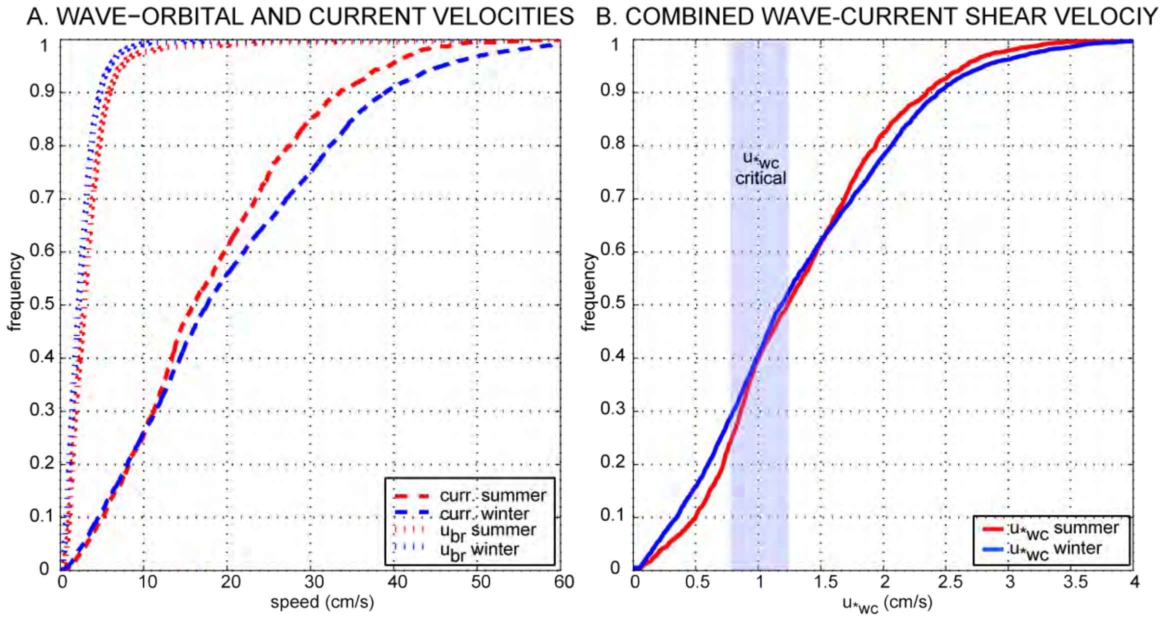

Figure 3. (a) Cumulative frequency distribution of wave-orbital velocities and hourly mean current speed at the long-term tripod site. Data from winter 2008-2009 and 2009-2010 are combined in blue, and summer 2009 values are shown in red. The distributions of wave-orbital velocities are similar in summer and winter, and slightly greater velocities occur more frequently in summer. Stronger currents are more frequent in winter. (b) The cumulative frequency distribution of the combined wave-current shear velocities for the same periods in summer (red) and winter (blue). The shaded box highlights the estimated range of the critical shear velocity for resuspension (between 0.8 and 1.2 cm/s).

RESULTS

Seasonal variations in bed stresses and suspended-sediment concentrations (Boldt et al., submitted)
In Willapa Bay, seasonal differences in hydrographic and hydrodynamic conditions affect the delivery of sediment to the system as well as the shear stress exerted on the seabed. The significant increase in precipitation events during winter introduces volumes of freshwater to the bay that are an order of magnitude greater during winter months. Between summer and winter, average wind speeds differed by only 1-2 m/s, but the greatest wind speeds occurred during winter and strong winds also blew more frequently. Additionally, currents reached greater velocities more frequently in winter (Fig. 3). Although greater wind speeds occurred during winter conditions, the near-bed wave-orbital velocities calculated at the long-term tripod site had similar mean values in summer (Fig. 3). The dominant wind direction in winter was from the south-southwest, and the channel geometry and topography surrounding the study area, particularly at the long-term tripod site, resulted in winter winds that were more likely to be fetch- and depth-limited. Thus, although average and peak wind speeds were greater during winter, the transfer of wave energy to the seabed was lessened due to the complex interaction of wind, water level, and the morphology of channels and landforms surrounding the tidal flat.

Because current velocities were an order of magnitude greater than wave-orbital velocities, combined wave-current shear velocities (u_{*wc}; Grant and Madsen, 1979) were strongly influenced by currents. However, the interaction between mean currents and wave-orbital velocities resulted in relatively equivalent ranges of u_{*wc} year-round (Fig. 3b). The distributions of u_{*wc} in both seasons indicate that approximately 50% of the time in both summer and winter conditions the combination of waves and currents exceeded an approximate threshold of resuspension. Greater concentrations of suspended sediment were observed in winter despite equivalent seasonally averaged bed shear velocities; mean winter water-column suspended-sediment concentrations exceeded mean summer concentrations by a factor of eight. Such seasonal differences result from greater sediment supply coinciding with periods of freshwater input. Within secondary channels, suspended-sediment concentrations (SSC) reached a peak value of 1800-2400 mg/L near the end of the ebb tide in winter conditions, and in summer were ~275 mg/L, a factor of ten less. The difference in wind speed and freshwater input prior to sampling suggests that more recently delivered sediment was available to be transported during winter, whereas in summer, readily transportable sediment was limited. In addition to differences in sediment supply from local rivers, biological activity acting on the surface of the mudflats affects sediment availability. The summer tidal flats are covered by eel grass and a film of microphytobenthos (Wheatcroft and Sanders, submitted), and thus, the presence of a biofilm and vegetation on the tidal flats during summer 2009 observations could help account for seasonal changes in the secondary-channel sediment load.

Sediment transport of channel-flat systems in a mesotidal mudflat (Nowacki and Ogston, submitted)
Detailed data from a typical tidal cycle (Fig. 4) illustrates the similarities and differences between dynamics on the flat surfaces and within the channels that bisect them. The characteristic flow and sediment regime in channels is one of flood dominance, but the magnitude of the imbalance varies under different conditions. Depending on water level relative to flat elevation, flow through channels is controlled either by bathymetric gradients and frictional conditions at the channel scale (below or at flat level; local control), or else via larger Shoalwater Bay-scale tidal circulation (above flat level; large-scale control). Channel morphology is the primary control on velocity and sediment dynamics throughout the flooding tide in both channels and flats, both early in the flood, when only the channel is inundated, and also later in the flood, when water level is above the flats. In contrast, during the early-to-middle parts of the ebb, flow in water masses over both flats and channels doesn't ”know” about the channel, and its direction is oriented with the the larger-scale ebb-tide forcing (approximately orthogonal to C channel). Only when water level is low enough for the channel bank bathymetric gradient to become important does the channel again become significant in exporting water and sediment from the flats. This imbalance of water and sediment imported and exported via the channels is a primary explanation for the persistent flood dominance of secondary channels: water and sediment entering the flats from the east via Bear channel will likely exit the flats via over-flat flow to the north.

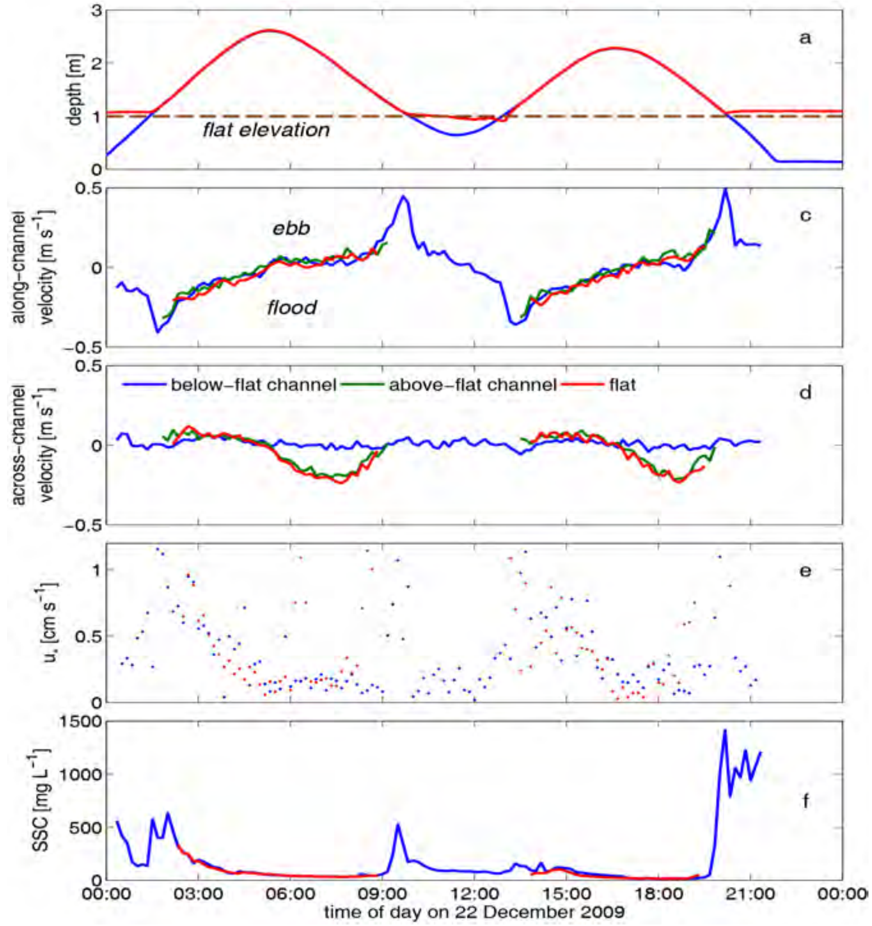

Figure 4. Time series of a typical tidal cycle in C channel and adjacent flat, showing (a) water surface elevation above the channel floor,(b) flow speed, (c) along-channel velocity, (d) across-channel velocity, (e) friction velocity computed using Reynolds stresses, and (f) suspended-sediment concentration.

In addition to this complex interaction between channel/flat morphology and tidal forcing, wind and precipitation alter system dynamics. Storms generally enhance the flood dominance of the channel; this result stands in contrast to previous studies in which wind events have been found to enhance ebb sediment transport (Christie et al., 1999, Dyer et al., 2000). Residual upstream sediment discharge in channels was enhanced by a factor of 2 - 6 during stormy periods due to increased sediment in suspension from flooding rivers and flat erosion (particularly during rain-on-flat events; Fig. 5), and increased flood-oriented residual flows due to the prevailing wind direction during winter storms.

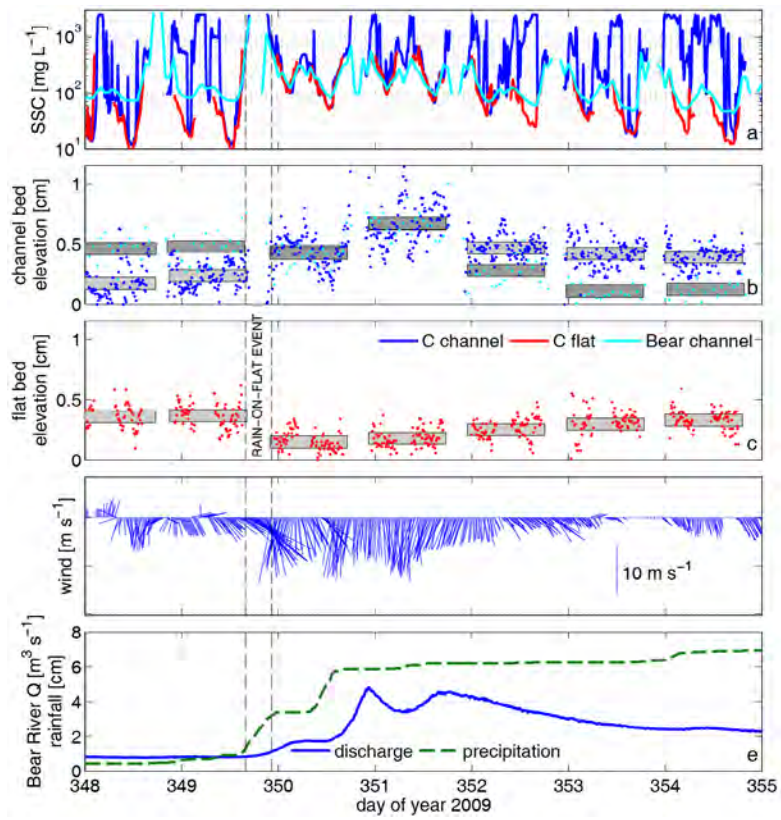

Figure 5. Rain-on-at event during December 2009. Period of rainfall onto exposed flats is indicated with dashed lines. (a) C channel SSC (blue), C at SSC (red), Bear channel SSC (cyan). (b) Bed elevation in C channel (blue) and Bear channel (cyan). (c) C at bed elevation. (d) Wind speed (blue) and direction (green). (e) Bear River discharge (blue) and cumulative precipitation (green).

Tidal pulse - velocity and sediment-flux (Nowacki & Ogston, submitted)

Tidal pulses are significant features in the flow and sediment regime of channels in Willapa Bay and are an important bathymetric modulation on tidal forcing. These short-lived velocity transients occur with great regularity when water levels cross the elevation of the flats (Fig. 6). As water level rises above the flat surface, the channel cross-sectional area increases rapidly as water spreads out across the flats. This rapid increase in area drives the pulse on flood. During ebbs, increased bottom friction from falling water level shifts flow on the flats from larger-scale tidal flow to flow controlled by the local bathymetric gradient. The resultant flow convergence results in a velocity pulse within the channel. The greatest flow speeds observed during each tidal cycle are associated with the pulse, and pulse-associated transport represents an important component of the water and sediment budget of C channel. While the duration of pulses represents only about 8% of total, pulses account for 33% (ebbs) and 21% (floods) of the total water discharge. Pulses are even more important to the sediment budget, representing 45% (ebbs) and 24% (floods) of the total.

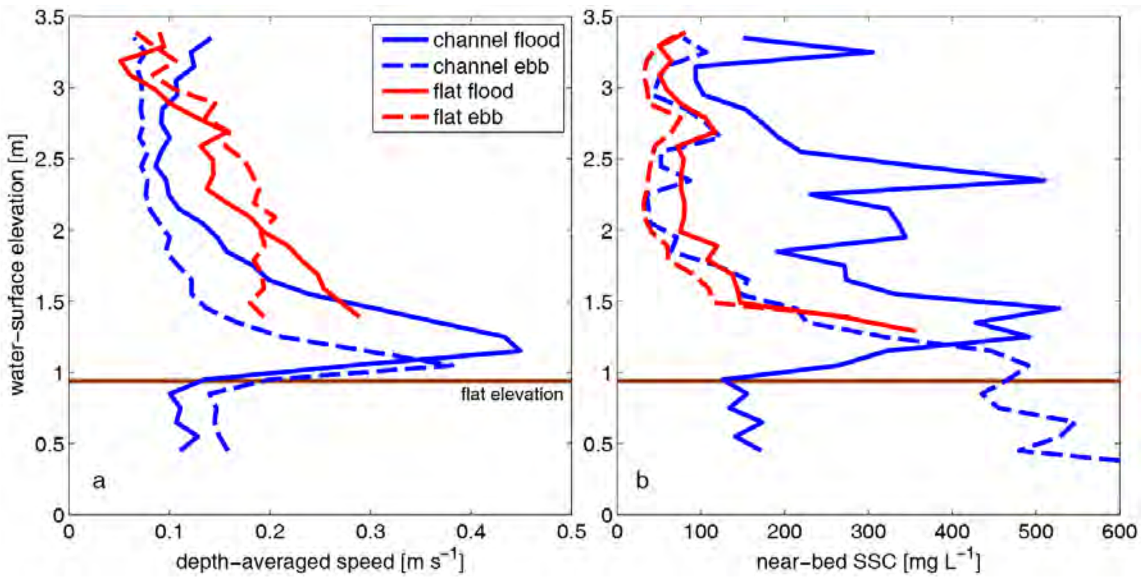

Figure 6: Median (a) depth-averaged speed and (b) near-bed SSC versus water-surface elevation in the below-flat channel (blue) and flat (red) illustrating the tidal velocity and SSC pulse. Flood data are indicated with solid lines; ebb data are indicated with dashed lines.

Throughout the flood, SSC in the channel is greater than on the flat, and this imbalance is enhanced by pulse dynamics. Thus, the channel serves as a temporary storage location (Boldt et al., submitted) of easily erodible sediment (Wiberg et al., submitted), and acts as a source for elevated channel SSC and landward sediment fluxes on the flood. Conversely, leading up to the ebb pulse, SSC values in both the channel and flat are similar, indicating that suspended sediment throughout the channel/flat system is well mixed before the ebb pulse, likely a result of the relative lack of activity in the below-flat channel. SSC in the channel reaches its peak during the ebb pulse and remains high despite the rapid decay of u_* following the pulse, suggesting that suspended sediment during this time is delivered from the adjacent tidal flats and upper channel flanks as processes at the water's edge resuspend sediment and advect it to the channel.

Comparison of observational data to numerical model results (Hsu et al, submitted)

Numerical model investigations conducted by Hsu et al. (submitted) provide intuition into mechanisms causing net landward and seaward sediment transport and focuses on the very shallow region of the tidal water's edge. As part of this work, a comparison of model results to field observations was undertaken. The data described in Nowacki and Ogston (submitted) suggest the presence of the water's edge front dynamic that is seen in both the RANS-VOF and ROMS models. On the flat, observed velocities and bed stresses are highest at the lowest tidal elevations monitored on both flood inundation and ebb dewatering, indicative of the water's edge processes (Fig. 7, right panels). Velocities are stronger on the flood than ebb tide, leading to greater peak magnitude of stress on the flood tide. This feature is consistent with idealized model results (Fig. 7d). The observed acoustic backscatter suggests significantly greater concentrations of sediment put in suspension on the flood tide than on the ebb under these field conditions. On the other hand, idealized model results suggest suspended sediment concentration during flood is only about 20~30% larger. Qualitatively, both field measured data and idealized model results indicate net landward transport of sediment.

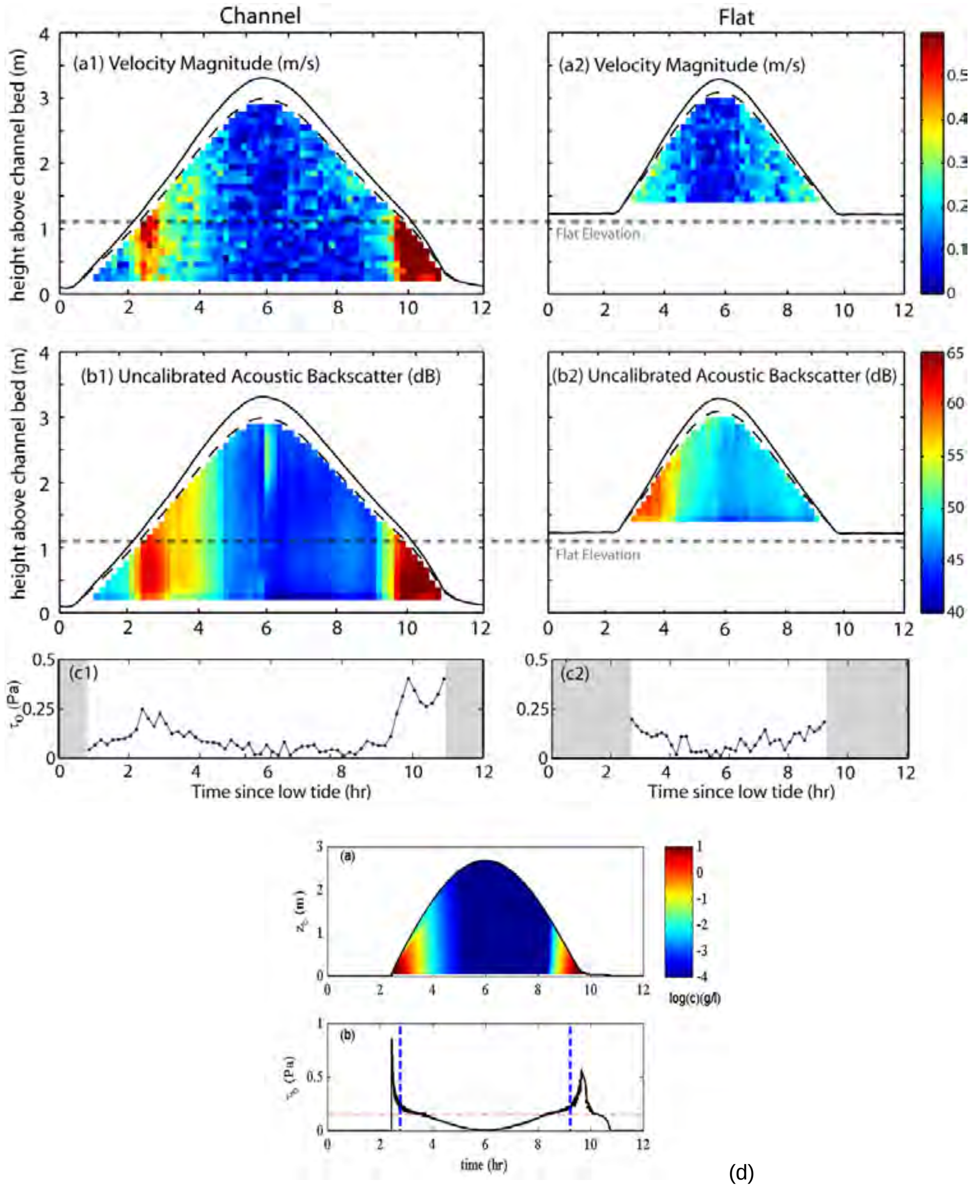

Figure 7: Example of time-series data collected in a channel (left panels) and on the nearby flat surface (right panels) in Willapa Bay on 23 July 2009 showing (a1, b1) profiles of velocity, (a2, b2) uncalibrated backscatter as a proxy for suspended sediment concentration, (c1, c2) estimated bed stress using the logarithmic law. (d) Times series from the RANS-VOF model of suspended sediment concentration and bed stress is shown for comparison. (Figure modified from Hsu et al., submitted.)

The channel data is more complex as it is dominated by three-dimensional effects of flow within the channel/flat complex and concentrations of sediment are associated with resuspension both in the channel and on the nearby flat (Fig. 7, left panels). At this location, the water's edge effect during flooding tide is not evident in the velocity data, but is suggested in the enhanced suspended sediment concentrations prior to the velocity pulse at mid tide. On the ebb, two peaks in bed stress are seen, one associated with the ebb-tide pulse (at ~9.8 hrs) discussed in Nowacki and Ogston (submitted), and the

other associated with the water's edge pulse (at ~11 hrs) that is predicted in the idealized model efforts. The critical role of the three-dimensional effects of channels in delivering sediment seaward is not incorporated in the idealized numerical modeling. The high resolution model results allow us to evaluate the important processes associated with the water's front that are difficult for sensors to capture in the field, but cannot be used to generalize all of the tidal-flat transport processes.

Export and retention of fluvial sediment on the Skagit River tidal flats (Webster et al., submitted)
In contrast to Willapa Bay, the seabed on the Skagit tidal flats is dominantly sandy with mud found only isolated in time (after floods) and space (near channels; on outer flat). Yet, an estimated 1-4 million tons of fine-grained sediment are discharged annually from the Skagit River onto the flat (Collins, 1998; Curran et al., this issue). Little of this mud is preserved on the flat and it can be inferred that physical transport processes on the flats are efficient at transporting sediment across the flat to the more distal parts of the dispersal system. In the south region (Fig. 8), the channel network consists of many similar sized braided channels oriented across the flat, and the instrumented tripods were centrally located within this network. Velocity data generally demonstrate that circulation is dominated by channelized across-flat (i.e., along-channel) flow. In contrast, in the northern region, the major distributary enters the flat and bifurcates into a channelized network that is constrained to the north, and the instrumented tripods were located on the southern edge of this branching region. Here, the net flow was less influenced by the channel network, and flow was oriented along the flat to the northwest, with a slight seaward component. Net flow at any point in the tidal flat is affected by both proximity to individual channels and placement within the channel network. Under equivalent fluvial conditions there are differing flood and ebb transport pathways through the braided-channel region. Of the factors that influence net flow and its heterogeneity across the flat, we conclude that geometry within the channel system and flows during major discharge events dominate, and physical processes of winds and waves play a lesser role.

The peak bed stresses occurred in the channel on ebb tide as the water level approached the flat elevation, and flow became channelized. Similar observations have been made in the muddy Willapa flats (Nowacki and Ogston, submitted). Two mechanisms of bed reworking occur within the south channel complex: currents creating asymmetric bedforms in the channel and waves creating symmetric ripples on the flat. The observed reworking in the top few centimeters of the seabed is likely a function of bedform migration, and illustrates that channel-bed sediment on the order of centimeters to tens of centimeters deep is mobile and fine-grained sediment is winnowed from the seabed and placed into suspension. Thus, recent fine-grained flood deposits can be erased from the record, and the signature of flood deposits within channels can be lost. While sediment is reworked vertically on the order of several centimeters over tidal time scales, sediment is reworked on the order of meters through lateral migration across the flat over decadal timescales. As channels migrate across the flat, channel splay deposits likely fill the abandoned channel remnants and these deposits can retain the fine-grained flood signatures over the period of channel filling.

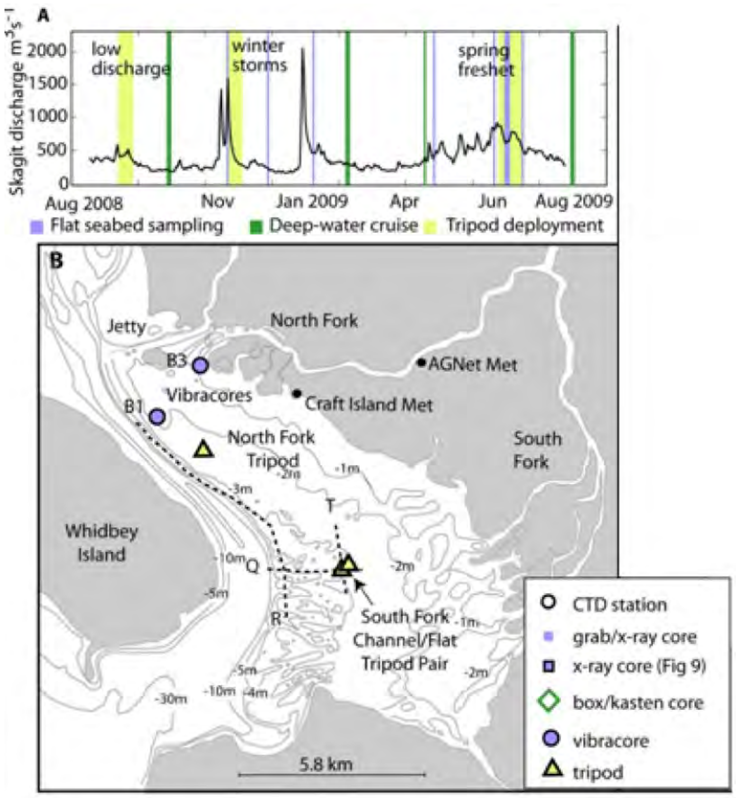

Figure 8. A) Skagit River discharge during the sampling period. Seasonal sampling scheme during periods of freshet, winter storms and low discharge are indicated by vertical lines. B) Skagit tidal flat with North and South Fork tripod locations (triangle) and tidal flat CTD transects (dashed line).

IMPACT/APPLICATIONS

Seabed properties of tidal flats are linked to the mechanisms and rates of transport and deposition on the flats and in the channels that bisect them, and our studies aim to enhance the ability to predict these properties in other areas. Our studies also provide insight for coastal management that can be transferred to other tidal-flat environments, allowing evaluation of the impacts of humans and invasive species on sediment dynamics. Both of the sites being studied have areas actively being restored, and we have consulted with teams undertaking these efforts.

RELATED PROJECTS

The Tidal Flats DRI projects are tightly knit. This work has provided interactions with all participants through field efforts, meetings, shared results and scientific discussions. This study is providing valuable collaborations with other research groups working under the Tidal Flats DRI, particularly by providing dynamic measurements to compare with models. The two-year-long monitoring package allows the group to monitor and observe during less-frequent events, gives context to the seasonal focus experiments and can aid the interpretation of imagery that has been obtained. Focus experiments

in Willapa Bay have been coordinated among a group of investigators. In addition to collaborations within the Tidal Flats DRI, the two instrumented tripods were deployed on the outer Skagit tidal flats in a study coordinated with an NSF project (Dr. C. Simenstad, UW) investigating ecosystem dynamics, and the size of ecotones for different species of benthic organisms.

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